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FORM PTO-1390 (REV. 11-2000) U S DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE

TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371

ATTORNEY'S DOCKET NUMBER: 7435-2

U.S. APPLICATION NO. (If known, see 37 CFR 1.5): 10/019354

INTERNATIONAL APPLICATION NO.	INTERNATIONAL FILING DATE	PRIORITY DATE CLAIMED
PCT/GB00/01601	04/25/00	04/23/99

TITLE OF INVENTION
LASER CAVITY

APPLICANT(S) FOR DO/EO/US
Alan Michael Cox, Lawrence Anthony William Gloster; Steve Haydn Lane

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. [X] This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. [ ] This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. [X] This is an express request to begin national examination procedures (35 U.S.C. 371(f)). The submission must include items (5), (6), (9) and (21) indicated below.
4. [X] The US has been elected by the expiration of 19 months from the priority date (Article 31).
5. [X] A copy of the International Application as filed (35 U.S.C. 371(c)(2))
   a. [ ] is attached hereto (required only if not communicated by the International Bureau).
   b. [X] has been communicated by the International Bureau.
   c. [ ] is not required, as the application was filed in the United States Receiving Office (RO/US).
6. [ ] An English language translation of the International Application as filed (35 U.S.C. 371(c)(2)).
   a. [ ] is attached hereto.
   b. [ ] has been previously submitted under 35 U.S.C. 154(d)(4).
7. [ ] Amendments to the claims of the International Aplication under PCT Article 19 (35 U.S.C. 371(c)(3))
   a. [ ] are attached hereto (required only if not communicated by the International Bureau).
   b. [ ] have been communicated by the International Bureau.
   c. [ ] have not been made; however, the time limit for making such amendments has NOT expired.
   d. [ ] have not been made and will not be made.
8. [ ] An English language translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371 (c)(3)).
9. [X] An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).
10. [ ] An English lanugage translation of the annexes of the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11 to 20 below concern document(s) or information included:

11. [ ] An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. [ ] An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. [X] A FIRST preliminary amendment.
14. [ ] A SECOND or SUBSEQUENT preliminary amendment.
15. [ ] A substitute specification.
16. [ ] A change of power of attorney and/or address letter.
17. [ ] A computer-readable form of the sequence listing in accordance with PCT Rule 13ter.2 and 35 U.S.C. 1.821 - 1.825.
18. [ ] A second copy of the published international application under 35 U.S.C. 154(d)(4).
19. [ ] A second copy of the English language translation of the international application under 35 U.S.C. 154(d)(4).
20. [X] Other items or information:
   PCT Published WO 01/08274 A1
   Int. Preliminary Examination Report

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Date of Deposit October 19, 2001
I hereby certify that this paper or fee is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37CFR § 1.10 on the date indicated above and is addressed to the Assistant Commissioner for Patents, Washington, D.C. 20231.
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Signature of person mailing paper or fee

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U.S. APPLICATION NO (if known, see 37 CFR 1.5)	INTERNATIONAL APPLICATION NO	ATTORNEY'S DOCKET NUMBER
10/019354	PCT/GB00/01601	7435-2

	CALCULATIONS	PTO USE ONLY
21. ☒ The following fees are submitted: **BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)):** Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO .... **$1000.00** International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO .... **$860.00** International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO .... **$710.00** International preliminary examination fee (37 CFR 1.482) paid to USPTO but all claims did not satisfy provisions of PCT Article 33(1)-(4) .... **$690.00** International preliminary examination fee (37 CFR 1.482) paid to USPTO and all claims satisfied provisions of PCT Article 33(1)-(4) **$100.00**		
ENTER APPROPRIATE BASIC FEE AMOUNT =	$ 860.00	
Surcharge of **$130.00** for furnishing the oath or declaration later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492(e)).	$	

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE	$	
Total claims	19 - 20 =	0	x **$18.00**	$	
Independent claims	1 - 3 =	0	x **$80.00**	$	
MULTIPLE DEPENDENT CLAIM(S) (if applicable)			+ **$270.00**	$	
TOTAL OF ABOVE CALCULATIONS =				$ 860.00	
☒ Applicant claims small entity status. See 37 CFR 1.27. The fees indicated above are reduced by 1/2. +				$ 430.00	
SUBTOTAL =				$ 430.00	
Processing fee of **$130.00** for furnishing the English translation later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492(f)).				$	
TOTAL NATIONAL FEE =				$ 430.00	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). **$40.00** per property +				$	
TOTAL FEES ENCLOSED =				$ 430.00	
				Amount to be refunded:	$
				charged:	$

a. ☒ A check in the amount of $ 430.00 to cover the above fees is enclosed.

b. ☐ Please charge my Deposit Account No. ____________ in the amount of $ __________ to cover the above fees. A duplicate copy of this sheet is enclosed.

c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 23-3030. A duplicate copy of this sheet is enclosed.

d. ☐ Fees are to be charged to a credit card. **WARNING:** Information on this form may become public. **Credit card information should not be included on this form.** Provide credit card information and authorization on PTO-2038.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137 (a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO:

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REGISTRATION NUMBER

7435-2

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re patent application of:	)	Express Mail No. EL683236635US
Alan Michael Cox et al.	)	October 19, 2001
Serial No. (unknown)	)	
Filed Herewith	)	
LASER CAVITY	)	
US National Stage of PCT/GB00/01601 Filed April 25, 2000	)	

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PRELIMINARY AMENDMENT

Hon. Assistant Commissioner of Patents

Washington, D.C. 20231

Sir:

Please enter the following amendments in the above-identified patent application. The Commissioner is hereby authorized to charge payment of any additional fees associated with this application or credit any overpayment to Deposit Account No. 23-3030.

IN THE CLAIMS

Please amend the claims to read as follows:

Clean Copy of Amended Claims:

1. A non-monolithic ring laser cavity comprising:

a. a gain medium;

b. a first polarisation rotation element arranged to rotate the polarisation of light propagating in the cavity with a predetermined handedness irrespective of the direction of propagation of the light;

c. a second polarisation rotation element arranged to rotate the polarisation of light propagating in the cavity with a handedness which is dependent upon the direction of propagation of the light;

d. a polarisation selection element arranged to cause loss to light propagating in the cavity, the loss being determined by the polarisation of light incident upon the polarisation selection element;

wherein the polarisation selection element comprises at least one mirror spaced away from the gain medium and arranged to reflect light at an angle displaced from the normal such that the reflectivity of the at least one mirror is sufficiently polarisation dependent that the laser oscillates uni-directionally.

2. A ring laser cavity according to claim 1, wherein the cavity comprises three or more mirrors.

3. A ring laser cavity according to claim 1, wherein the cavity comprises four or more mirrors.

4. A ring laser cavity according to claim 3, wherein the first polarisation rotation element comprises one mirror of the cavity located such that the point of reflection of the beam is out of the plane defined by the points of reflection of three of the other mirrors.

5. A ring laser cavity according to claim 1, wherein the second polarisation rotation element comprises a Faraday rotator.

6. A ring laser cavity according to claim 1, wherein the angle of reflection of the at least one angled mirror is greater than 25 degrees.

7. A ring laser cavity according to claim 6, wherein the angle of reflection of the at least one angled mirror is between 40 and 55 degrees.

8. A ring laser cavity according to claim 7, wherein the angle of reflection of the at least one angled mirror is greater than 55 degrees.

9. A ring laser cavity according to claim 1, wherein the at least one angled mirror comprises two mirrors arranged to reflect light at an angle displaced from the normal such that the cumulative reflectivity of the two mirrors is sufficiently polarisation dependent that the laser oscillates uni-directionally.

10. A ring laser cavity according to claim 1, wherein one of the mirrors is concave, and is arranged to reflect light at less than 8 degrees from the normal.

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11. A ring laser cavity according to claim 10, wherein the concave mirror is arranged to reflect light at less than 4 degrees from the normal.

12. A ring laser cavity according to claim 1, wherein the cavity further includes a frequency doubling element arranged to double the frequency of light generated by the laser gain medium.

13. A ring laser cavity according to claim 12, wherein the frequency doubling element comprises a crystal of Potassium Titanyl Phosphate.

14. A ring laser cavity according to claim 1, wherein the gain medium is excited by light generated by one or more semiconductor devices.

15. A ring laser cavity according to claim 14, wherein the light generated by the one or more semiconductor devices is directed into the gain medium such that it has an absorption profile in the gain medium which substantially corresponds to the profile of the laser mode in the gain medium.

16. A ring laser cavity according to claim 14, wherein the one or more semiconductor devices is arranged to direct light into the gain medium by illumination from the sides of the gain medium.

17. A ring laser cavity according to claim 1, wherein the gain medium comprises a crystal of Yttrium Aluminium Garnet (YAG) doped with a suitable element.

18. A ring laser cavity according to claim 1, wherein at least two mirrors are spaced away from the gain medium.

19. A ring laser cavity according to claim 18, wherein at least three mirrors are spaced away from the gain medium.

Version with Markings to Show Changes Made

1. A non-monolithic ring laser cavity comprising:

a. a gain medium;

b. a first polarisation rotation element arranged to rotate the polarisation of light propagating in the cavity with a predetermined handedness irrespective of the direction of propagation of the light;

c. a second polarisation rotation element arranged to rotate the polarisation of light propagating in the cavity with a handedness which is dependent upon the direction of propagation of the light;

d. a polarisation selection element arranged to cause loss to light propagating in the cavity, the loss being determined by the polarisation of light incident upon the polarisation selection element;

wherein the polarisation selection element comprises at least one mirror spaced away from the gain medium and arranged to reflect light at an angle displaced from the normal such that the reflectivity of the at least one mirror is sufficiently polarisation dependent that the laser oscillates uni-directionally.

2. A ring laser cavity according to claim 1, wherein the cavity comprises three or more mirrors.

3. A ring laser cavity according to claim 1~~ or 2~~, wherein the cavity comprises four or more mirrors.

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4. A ring laser cavity according to claim 3, wherein the first polarisation rotation element comprises one mirror of the cavity located such that the point of reflection of the beam is out of the plane defined by the points of reflection of three of the other mirrors.

5. A ring laser cavity according to ~~any of claims 1 to 4,~~claim 1, wherein the second polarisation rotation element comprises a Faraday rotator.

6. A ring laser cavity according to ~~any preceding claim,~~claim 1, wherein the angle of reflection of the at least one angled mirror is greater than 25 degrees.

7. A ring laser cavity according to claim 6, wherein the angle of reflection of the at least one angled mirror is between 40 and 55 degrees.

8. A ring laser cavity according to claim 7, wherein the angle of reflection of the at least one angled mirror is greater than 55 degrees.

9. A ring laser cavity according to ~~any preceding claim,~~claim 1, wherein the at least one angled mirror comprises two mirrors arranged to reflect light at an angle displaced from the normal such that the cumulative reflectivity of the two mirrors is sufficiently polarisation dependent that the laser oscillates uni-directionally.

10. A ring laser cavity according to ~~any preceding claim,~~claim 1, wherein one of the mirrors is concave, and is arranged to reflect light at less than 8 degrees from the normal.

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11. A ring laser cavity according to claim 10, wherein the concave mirror is arranged to reflect light at less than 4 degrees from the normal.

12. A ring laser cavity according to ~~any preceding claim,~~claim 1, wherein the cavity further includes a frequency doubling element arranged to double the frequency of light generated by the laser gain medium.

13. A ring laser cavity according to claim 12, wherein the frequency doubling element comprises a crystal of Potassium Titanyl Phosphate.

14. A ring laser cavity according to ~~any preceding claim,~~claim 1, wherein the gain medium is excited by light generated by one or more semiconductor devices.

15. A ring laser cavity according to claim 14, wherein the light generated by the one or more semiconductor devices is directed into the gain medium such that it has an absorption profile in the gain medium which substantially corresponds to the profile of the laser mode in the gain medium.

16. A ring laser cavity according to claim 14, wherein the one or more semiconductor devices is arranged to direct light into the gain medium by illumination from the sides of the gain medium.

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17. A ring laser cavity according to ~~any preceding claim,~~claim 1, wherein the gain medium comprises a crystal of Yttrium Aluminium Garnet (YAG) doped with a suitable element.

18. A ring laser cavity according to ~~any preceding claim,~~claim 1, wherein at least two mirrors are spaced away from the gain medium.

19. A ring laser cavity according to claim 18, wherein at least three mirrors are spaced away from the gain medium.

~~20. A ring laser cavity substantially as hereinbefore described with reference to the accompanying drawing.~~

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REMARKS

Consideration and allowance of the above application are respectfully requested.

Respectfully submitted,

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Laser Cavity

The present invention relates to a laser cavity, and in particular to a ring laser cavity.

Laser cavities configured as rings have been widely used to eliminate a problem known as spatial hole burning. Spatial hole burning occurs in laser cavities which allow light to propagate in opposing directions within a gain medium, for example in a linear laser cavity. Light in such a laser cavity forms a standing wave, which selectively depletes the gain medium according to the localised intensity distribution of this standing wave (spatial hole burning). The effect of the spatial hole burning is to make several longitudinal modes of the laser cavity oscillate simultaneously in a homogeneously broadened laser (which may otherwise exhibit single longitudinal mode behaviour), thereby compromising the spectral purity of the laser. This multimode behaviour can cause instabilities in laser systems that are intra-cavity doubled (T. Baer, 'Large-amplitude fluctuations due to longitudinal mode coupling in diode-pumped intracavity-doubled Nd:YAG lasers,' J. Opt. Soc. Am. B 3, 1175 (1986)).

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In a ring laser, light generated by stimulated emission in the gain medium is made to propagate in one direction only around the ring, thereby preventing the formation of standing waves and avoiding the resulting spatial hole burning in the gain medium. Since there is no spatial hole burning in the gain medium, the laser may oscillate in a single longitudinal mode (provided that the gain medium is predominantly homogeneously broadened). The single longitudinal mode in an intra-cavity doubled, uni-directional ring laser is considerably more stable than the multiple modes seen in a conventional intra-cavity doubled laser cavity, and is significantly less sensitive to environmental changes, such as temperature fluctuations.

If light is allowed to propagate in both directions in a ring cavity, spatial hole burning can occur and the main advantages of a ring laser cavity over a linear laser cavity are lost.

In order to allow the light to propagate in only one direction around a ring laser cavity, the loss suffered by light propagating in an unwanted direction must be made greater than the loss suffered by light propagating in the preferred direction. Provided that the difference between the two losses is sufficient, the laser cavity will oscillate in the preferred direction only.

In order to impose differing losses on light propagating in opposite directions around a ring laser cavity, it is necessary to combine three effects. These are as follows :

1) Rotation of the polarisation of the light with the same handedness (with respect to its direction of travel) whichever direction the light is propagating around the ring laser cavity (for example using a quartz plate). This is known as reciprocal rotation.
2) Right handed rotation of the polarisation of light propagating in a first preferred direction and left handed rotation of the polarisation of light propagating in an unwanted, opposite direction around the ring laser cavity (or vice-versa). This can be achieved using a Faraday rotator . This is known as non-reciprocal rotation.
3) Selective transmission of light having polarisation in a predetermined plane (for example using a Brewster-angled plate). This effect is referred to as polarisation selectivity.

In a system incorporating the above three effects, a beam propagating in the preferred direction will have its polarisation rotated away from and then back towards its initial polarisation orientation, and will be transmitted with relatively low loss by the polarisation selectivity. In contrast to this, a beam propagating in the unwanted direction will have its polarisation rotated in one direction and then further rotated in the same direction (away from the initial polarisation orientation), and will suffer a greater loss due to the polarisation selectivity.

When designing laser cavities for efficient intra-cavity doubling it is necessary to achieve a high cavity finesse to keep the loss suffered by an oscillating mode in the cavity to a minimum, since any increase of the loss will cause a corresponding decrease of finesse and, therefore, efficiency.

It is an object of the present invention to provide a ring laser cavity having a low loss.

According to the invention there is provided a non-monolithic ring laser cavity comprising:

a. a gain medium;

b. a first polarisation rotation element arranged to rotate the polarisation of light propagating in the cavity with a predetermined handedness irrespective of the direction of propagation of the light;

c. a second polarisation rotation element arranged to rotate the polarisation of light propagating in the cavity with a handedness which is dependent upon the direction of propagation of the light;

d. a polarisation selection element arranged to cause loss to light propagating in the cavity, the loss being determined by the polarisation of light incident upon the polarisation selection element;

wherein the polarisation selection element comprises at least one mirror spaced away from the gain medium and arranged to reflect light at an angle displaced from the normal such that the reflectivity of the at least one mirror is sufficiently polarisation dependent that the laser oscillates uni-directionally.

When light is reflected from a mirror at an angle displaced from the normal, the mirror may have a greater reflectivity for s-polarised light than for p-polarised light. At large enough angles of incidence, the reflectivity of a mirror will become sufficiently polarisation dependent that it can act as the required polarisation selection element such that a ring laser incorporating the mirror is forced to oscillate uni-directionally (two or more mirrors arranged to reflect at lesser angles may provide an equivalent cumulative effect). The term 'sufficiently polarisation dependent' is

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intended to mean that uni-directional oscillation is achieved without introducing an extra polarisation selection element into the cavity, for example a Brewster plate or a Brewster angled window at one or both ends of a gain medium. The term 'sufficiently polarisation dependent' is not intended to exclude a ring laser cavity wherein the polarisation dependent reflection of the at least one mirror is supplemented with polarisation selectivity provided by a natural polarisation preference of a gain medium in the ring laser cavity.

The invention allows the construction of a low loss, high finesse ring laser cavity, since the introduction of an extra polarisation selection element is avoided. High finesse is particularly important if the laser cavity includes a frequency-doubling element. A further advantage of the invention is that it is possible to achieve a small reflection angle on an output coupling mirror (which is often curved). This small reflection angle is beneficial because the astigmatic effects caused by the output mirror are kept to a minimum.

The ring laser cavity preferably comprises three or more mirrors, and most preferably comprises four mirrors (although more mirrors may be used). Where four or more mirrors are used, the first polarisation rotation element may comprise one mirror of the cavity located such that the point of reflection of the beam is out of the plane defined by the points of reflection of three of the other mirrors. This is known as a non-planar ring oscillator (NPRO).

Preferably, the second polarisation rotation element comprises a Faraday rotator.

Preferably, the angle of reflection of the at least one angled mirror is greater than 25 degrees. The angle is measured relative to the normal from the mirror. The angle is chosen to be greater than 25 degrees in order to provide the polarisation selectivity required by the invention.

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Preferably, the angle of reflection of the at least one angled mirror is between 40 degrees and 55 degrees. High reflectivity dielectric mirrors configured to reflect at approximately 45 degrees are available commercially 'off the shelf', and these may be used to reflect with good efficiency from 40 degrees to 55 degrees.

The angle of reflection of the at least one angled mirror may be greater than 55 degrees.

The at least one angled mirror may comprise two mirrors arranged to reflect light at an angle displaced from the normal such that the cumulative reflectivity of the two mirrors is sufficiently polarisation dependent that the laser oscillates uni-directionally.

The polarisation selection element may comprise two consecutively reflecting angled mirrors.

Preferably, one of the mirrors is concave, and is arranged to reflect light at less than 8 degrees from the normal. More preferably, the concave mirror is arranged to reflect light at less than 4 degrees from the normal. This reduces the astigmatic effect of the concave mirror (which is commonly an output coupler).

Suitably, the cavity further includes a frequency doubling element arranged to double the frequency of light generated by the laser gain medium.

Suitably, the frequency doubling element comprises a crystal of Potassium Titanyl Phosphate (KTP). Alternatively, the frequency doubling element comprises a Potassium Niobate ($KNbO_3$) crystal. Alternatively, the frequency doubling element comprises a crystal of Lithium Triborate (LBO).

Preferably, the gain medium is excited by light generated by one or more semiconductor devices. A semiconductor device may for example be a laser diode.

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Suitably, the light generated by the one or more semiconductor devices is directed into the gain medium such that it has an absorption profile in the gain medium which substantially corresponds to the profile of the laser mode in the gain medium.

Alternatively, the one or more semiconductor devices are arranged to direct light into the gain medium by illumination from the sides of the gain medium.

Suitably, the gain medium comprises a crystal of Yttrium Aluminium Garnet (YAG) doped with a suitable element. The doping element may be for example Neodymium. The gain medium may alternatively be Vanadate (YVO_4) doped with a suitable element, for example Neodymium. Alternatively, the gain medium may be a material commonly known as Lanthanum Scandium Borate (LSB), doped with a suitable element, for example Neodymium.

The invention is not intended to include monolithic laser cavities. A monolithic laser cavity is a laser cavity in which an entire optical cavity is formed from a single crystal or glass element, or crystals or glass elements optically bonded together to form a laser cavity, such that intra-cavity laser light travels only through the crystal or glass elements or elements. Monolithic lasers are not suited to the generation of frequency doubled light using an intra-cavity frequency doubling element.

Specific embodiments of the invention will now be described by way of example only, with reference to the accompanying drawing which shows schematically a laser cavity according to the invention.

The drawing shows a first embodiment of the invention; a laser cavity comprising a gain medium 1, a Faraday rotator 2, and a non-linear crystal 3, all located in a cavity defined by four mirrors 4-7. In the illustrated embodiment the gain medium is a rod of Nd:YAG, which emits light at 1064nm. The non-linear crystal 3 comprises a rod of Potassium Titanyl Phosphate (KTP) which is arranged to

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frequency-double light in the cavity from 1064nm to 532nm. Mirror 4 is designed to be highly reflecting at the fundamental wavelength (in this case 1064 nm). Mirrors 5 and 6 are highly reflecting at 1064 nm for a reflection angle of typically 45 degrees from the normal. Mirror 7 is highly reflecting at 1064 nm and is highly transmissive at 532 nm. In an alternative embodiment of the invention the cavity may be constructed without the non-linear crystal present. In this case the mirror 7 is coated to partially transmit 1064 nm light, to allow a proportion of the 1064 nm light to be output from the cavity.

The Nd:YAG rod 1 is pumped optically using, for example, a diode laser (not shown) with sufficient intensity that laser oscillation of light at 1064nm occurs in the cavity. The optical pump light provided by the diode laser is preferably arranged such that an absorption profile of the pump light within the Nd:YAG rod 1 is substantially matched with the profile of the laser mode in the Nd:YAG rod 1. The diode laser may alternatively be arranged to direct light into the gain medium by illumination from the sides of the gain medium (this arrangement is not preferred because it is less efficient).

A portion of the 1064nm light (typically <0.5% per pass) is frequency doubled by the KTP rod 3, and this frequency-doubled light is emitted as a coherent beam from the output coupler 7.

At least one mirror, preferably the output coupler 7, is concave to maintain a stable oscillating mode of the laser cavity. The mirror 4 facing the output coupler 7 may also be concave.

If no directionally selective elements are included in the cavity, then oscillating modes will be able to propagate in opposite directions around the cavity, and this will lead to spatial hole burning in the gain medium 1. In order to make the light propagate in only one direction around the laser cavity, the loss suffered by light propagating in an unwanted direction is made greater than the loss suffered by light propagating in the preferred direction. The required directional selectivity is provided

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by a combination of the polarisation rotation caused by the Faraday rotator 2, polarisation rotation caused by locating one of the mirrors outside of a plane defined by the other three, and polarisation selectivity obtained by making two of the mirrors 5,6 reflect light at approximately 45 degrees to the normal.

The Faraday rotator 2 causes a right-hand polarisation rotation of light propagating in a preferred direction in the cavity, and causes a left-hand polarisation rotation of light propagating in an unwanted, opposite, direction. The out-of-plane nature of the cavity causes a polarisation rotation of the light which is always left-handed regardless of the direction of propagation of the light around the ring. Thus, the polarisation of light propagating in the preferred direction suffers relatively little net polarisation rotation from the combined effect of the Faraday rotator 2 and the out-of-plane nature of the cavity, whereas the polarisation of light propagating in the unwanted, opposite, direction suffers a greater net rotation.

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The reflectivity of the mirrors 5,6 arranged to reflect light at 45 degrees (hereafter referred to as the angled mirrors) is typically greater for s-polarised light than it is for p-polarised light. Light which propagates around the cavity in the preferred direction, provided that it is initially s-polarised, will be relatively unaffected by the combined effect of the Faraday rotator 2 and the out-of-plane nature of the cavity, and will be reflected with high reflectivity from the mirrors 5,6. Light which propagates around the cavity in the unwanted direction, if initially s-polarised, will be rotated by the combined effects of the Faraday rotator 2 and the out-of-plane nature of the cavity, such that it has a degree of p-polarisation, and will be reflected with a lesser reflectivity from the angled mirrors 5,6.

The angled mirrors are dielectric coated mirrors, and can typically reflect s-polarised light with a loss of <0.05%, and p-polarised light with a loss of typically 1-3%. This polarisation selectivity is arranged to be sufficient to cause enough loss to light propagating in the unwanted direction that oscillation of light propagating in that direction in the cavity is suppressed. Spatial hole burning is thus suppressed and the

cavity can oscillate in a single longitudinal mode as the gain medium is predominantly homogeneously broadened.

The use of the two angled mirrors 5,6 is advantageous because it does not introduce significant loss into the cavity. This is particularly important when the cavity includes a frequency-doubling crystal (as shown in the drawing), because the efficiency of the frequency doubling process relies upon a high cavity finesse, which in turn is dependent upon the cavity having a low loss. In a high finesse laser cavity, the intensity of light inside the cavity can be so high that loss caused by the introduction of a polarisation selection element is unsatisfactory. Even an additional loss of 0.1%, for example due to the introduction of a Brewster plate into the cavity, may cause unacceptable deterioration of the finesse of the cavity. Ideally, most of the loss in the cavity should occur due to frequency conversion in the KTP rod 3, leading to light being usefully lost through the output coupler 7. This conversion is typically <0.5% efficient.

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The angled mirrors 5,6 are manufactured to provide high reflectivity of light at around 45 degrees incidence relative to the normals of the mirrors. Mirrors of this type are readily available, and are relatively inexpensive. However, mirrors arranged to reflect light at angles other than 45 degrees may be used. In general, the reflectivity with regard to s-polarised light is easily made high at angles of incidence greater than 45 degrees, but the reflectivity of the p-polarised light is usually reduced, thereby enhancing the polarisation selectivity. In contrast to this, the polarisation selectivity is usually small for mirrors reflecting light at less than 20 degrees to the normal. At zero degrees, there is typically no appreciable selectivity at all.

Where the polarisation selectivity is enhanced, the degree of polarisation rotation induced by the Faraday rotator 2 may be reduced without compromising the uni-directional operation of the laser. This is advantageous because it allows a shorter, and therefore cheaper, Faraday rotator crystal to be used. Similarly, when the polarisation selectivity is enhanced, the degree of polarisation rotation induced by the out-of-plane cavity may be reduced.

Ideally, light propagating in the preferred direction is almost exclusively s-polarised when it is reflected by both of the angled mirrors 5 and 6.

Often, as the angle of reflection from the normal increases, it is possible to achieve lower loss for an s-polarised beam reflecting off an appropriately designed mirror. The invention is therefore advantageous because the angled mirrors 5,6 allow the reduction of losses suffered by s-polarised light.

The Faraday rotator 2 consists of a strong magnet and a material with a large Verdet constant. This constant links the polarisation rotation to the magnetic field applied to the material and the length of the crystal. Typically, the polarisation rotation introduced by the Faraday rotator 2 is a few degrees (less than 10 degrees), as is the corresponding rotation caused by the out of plane nature of the cavity. Certain gain media can also be used as Faraday rotators e.g. Nd:YAG.

The frequency doubling crystal will introduce a non-linear coupling loss of typically 0.5 % in the preferred direction (by conversion from 1064 nm to 532 nm); a loss which is intensity dependent and is not present for the opposite, unwanted propagation direction. The differential loss due to the polarisation control described earlier must be greater than this non-linear loss in order to ensure that the laser robustly oscillates only in the correct direction around the ring.

A further advantage of the cavity configuration shown in the drawing is that a small reflectance angle ϑ is subtended at the curved output coupler 7, as compared to the angle subtended in conventional ring laser cavities. The reduction of the reflectance angle ϑ reduces the astigmatic effect of the curved mirror 7.

It will be appreciated that the direction of polarisation rotation induced by the Faraday rotator 2 may be reversed by reversing the direction of the applied magnetic field, and that the preferred direction of propagation in the ring laser cavity may be correspondingly reversed.

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The gain medium (in this example Nd:YAG) may be located between the frequency doubling crystal 3 and the mirror 4.

It will be understood that the invention is not limited to ring laser cavities having a Nd:YAG gain medium, but may be applied to a ring laser cavity having any other suitable gain medium. The gain medium may be Vanadate (YVO_4) doped with a suitable element, for example Neodymium. Alternatively, the gain medium may be a material commonly known as LSB, doped with a suitable element, for example Neodymium.

Although the described embodiment of the invention includes a KTP frequency doubling element, any other suitable frequency doubling element may be used, for example a Potassium Niobate ($KNbO_3$) crystal, or a crystal of the material commonly known as LBO.

Although the described embodiment of the invention includes a diode laser operating as an optical pump, the gain medium may be excited by any suitable means.

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Claims

1. A non-monolithic ring laser cavity comprising:

a. a gain medium;

b. a first polarisation rotation element arranged to rotate the polarisation of light propagating in the cavity with a predetermined handedness irrespective of the direction of propagation of the light;

c. a second polarisation rotation element arranged to rotate the polarisation of light propagating in the cavity with a handedness which is dependent upon the direction of propagation of the light;

d. a polarisation selection element arranged to cause loss to light propagating in the cavity, the loss being determined by the polarisation of light incident upon the polarisation selection element;

wherein the polarisation selection element comprises at least one mirror spaced away from the gain medium and arranged to reflect light at an angle displaced from the normal such that the reflectivity of the at least one mirror is sufficiently polarisation dependent that the laser oscillates uni-directionally.

2. A ring laser cavity according to claim 1, wherein the cavity comprises three or more mirrors.

3. A ring laser cavity according to claim 1 or 2, wherein the cavity comprises four or more mirrors.

4. A ring laser cavity according to claim 3, wherein the first polarisation rotation element comprises one mirror of the cavity located such that the point of reflection of the beam is out of the plane defined by the points of reflection of three of the other mirrors.

5. A ring laser cavity according to any of claims 1 to 4, wherein the second polarisation rotation element comprises a Faraday rotator.

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6. A ring laser cavity according to any preceding claim, wherein the angle of reflection of the at least one angled mirror is greater than 25 degrees.

7. A ring laser cavity according to claim 6, wherein the angle of reflection of the at least one angled mirror is between 40 and 55 degrees.

8. A ring laser cavity according to claim 7, wherein the angle of reflection of the at least one angled mirror is greater than 55 degrees.

9. A ring laser cavity according to any preceding claim, wherein the at least one angled mirror comprises two mirrors arranged to reflect light at an angle displaced from the normal such that the cumulative reflectivity of the two mirrors is sufficiently polarisation dependent that the laser oscillates uni-directionally.

10. A ring laser cavity according to any preceding claim, wherein one of the mirrors is concave, and is arranged to reflect light at less than 8 degrees from the normal.

11. A ring laser cavity according to claim 10, wherein the concave mirror is arranged to reflect light at less than 4 degrees from the normal.

12. A ring laser cavity according to any preceding claim, wherein the cavity further includes a frequency doubling element arranged to double the frequency of light generated by the laser gain medium.

13. A ring laser cavity according to claim 12, wherein the frequency doubling element comprises a crystal of Potassium Titanyl Phosphate.

14. A ring laser cavity according to any preceding claim, wherein the gain medium is excited by light generated by one or more semiconductor devices.

15. A ring laser cavity according to claim 14, wherein the light generated by the one or more semiconductor devices is directed into the gain medium such that it has an absorption profile in the gain medium which substantially corresponds to the profile of the laser mode in the gain medium.

16. A ring laser cavity according to claim 14, wherein the one or more semiconductor devices is arranged to direct light into the gain medium by illumination from the sides of the gain medium.

17. A ring laser cavity according to any preceding claim, wherein the gain medium comprises a crystal of Yttrium Aluminium Garnet (YAG) doped with a suitable element.

18. A ring laser cavity according to any preceding claim, wherein at least two mirrors are spaced away from the gain medium.

19. A ring laser cavity according to claim 18, wherein at least three mirrors are spaced away from the gain medium.

20. A ring laser cavity substantially as hereinbefore described with reference to the accompanying drawing.

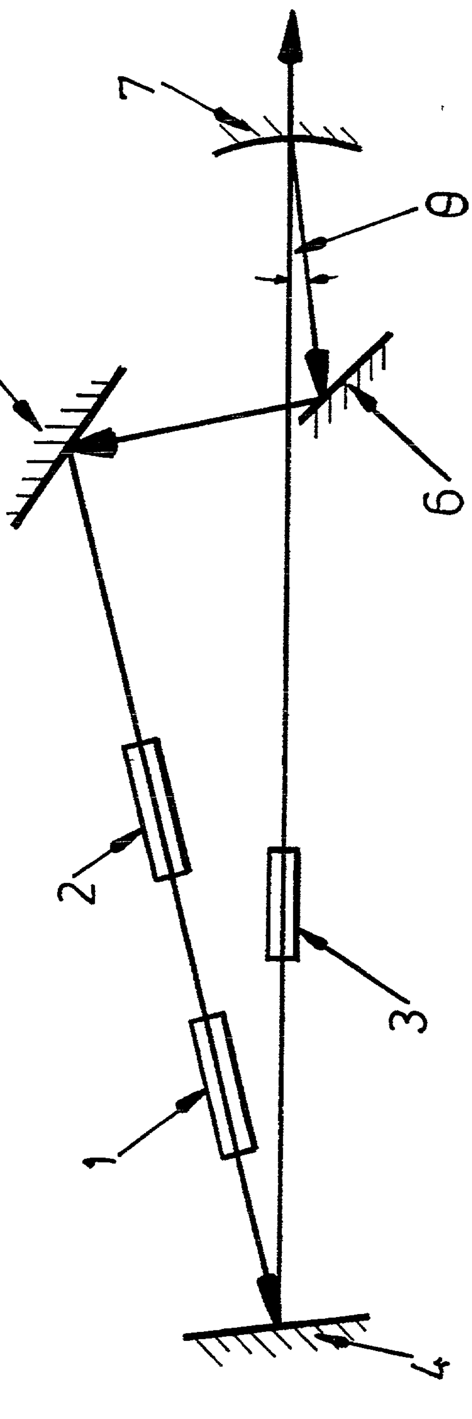

FIG. 1

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WENMM SB/01 (2-99)

DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION	Attorney Docket Number	7435-2
	First Named Inventor	Alan Michael Cox

OIPE JC181 APR 0 5 2002 PATENT & TRADEMARK OFFICE

☐ Declaration submitted with Initial Filing

☒ Declaration Submitted after Initial Filing (surcharge (37 CFR 1.16(e)) required)

COMPLETE IF KNOWN	
Application No.	10/019,354
Filing Date	
Group Art Unit	
Examiner's Name	

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

LASER CAVITY

the specification of which
(check one)

☐ is attached hereto.

☒ Was filed on April 24, 2000 as United States Application No. or

PCT International Application No. PCT/GB00/01601

☐ And was amended on ____________________ (if applicable).

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the patentability of this application in accordance with Title 37, Code of Federal Regulations, §1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, §119(a)-(d) or 365(b) of any foreign application(s) for patent or inventor's certificate, or 365(a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

Prior Foreign Application Number(s)	Country	Foreign Filing Date (MM/DD/YY)	Priority Not Claimed	Certified Copy Attached?	
				Yes	No
PCT/GB00/01601	PCT	04/25/00		☐	☒
9909252.0	GB	04/23/99		☐	☒

I hereby claim the benefit under 35 U.S.C. 119(e) of any United States provisional application(s) listed below.

Application Number(s)	Filing Date (MM/DD/YYYY)

☐ Additional provisional application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto.

APR 0 5 2002 PATENT & TRADEMARK OFFICE

I hereby claim the benefit under Title 35, United States Code, §120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, §112, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, §1.56 which occurred between the filing date of the prior application and the national or PCT international filing date of this application:

U.S. Parent Application or PCT Parent Number	Parent Filing Date (MM/DD/YYYY)	Parent Patent Number (if applicable)

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As a named inventor, I hereby appoint the following registered practitioner(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith:

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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WENMM SB/02C (3-97)

DECLARATION

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(Supplemental Sheet)

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